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Research article

Modelling convectional oven drying characteristics and energy consumption of dehydrated yam (*Dioscorea rotundata*) chips

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ABSTRACT

The influence of pre-treatments and different dehydrating temperatures on the drying dynamics, energy consumption, and quality attribute of yam chips was studied. Dehydration was executed employing a convectional oven dryer under four temperatures (50, 60, 70, and 80 °C) and 2.0 m/s air velocity. Yam chips were subjected to pre-treatment conditions of blanching (for 1, 2, 3, 4, and 5 min), citric acid (1 and 5 %), and ascorbic acid (1 and 5 %) solutions whereas, untreated yam chips samples served as the control. Dehydrated yam chips were further assessed for textural and colour properties. The drying rate was found to be faster at a higher temperature of 80 °C compared to lower temperatures of 50, 60, and 70 °C. The asymptotic model was established to be the suitable descriptive model for predicting moisture profile in the pre-treated yam chips based on highest R^2 values (0.995–0.999), lowest χ^2 values (4.422–18.498), and the root mean square error (RMSE) values (2.103–4.30). Pre-treatment and drying temperature had a significant ($p < 0.05$) impact on the hardness and colour of dehydrated yam chips. Blanching at 4 min yielded yam chips with most preferred texture (hardness: 81.3 N) and lightness (L^*) in colour values (71.07 %) after drying compared to other pre-treated samples. The effective moisture diffusivity values of the pre-treated samples were in the range of 5.17294×10^{-9}m^2/s to 1.10143×10^{-8}m^2/s for 5 % citric acid samples at 50 °C and all pre-treated samples at 80 °C respectively. The general findings of the study indicated a least energy usage of 43.68 kWh as a cost-effective method of drying. Also, 4 min blanching, 5 % citric acid, and 1 % ascorbic acid at 80 °C were found to be the optimum conditions for pre-treating yam chips based on lower energy level consumption rates and improved sensory properties thus attributing to the quality of the dried yam chips.

1. Introduction

Yam (*Dioscorea* spp.) is a dioecious species and monocotyledonous crop of the family *Dioscoreaceae* possessing a climbing vine and twining and sprawling stem cultivated for its starchy underground tubers. Globally, yam is predominantly cultivated in the tropical

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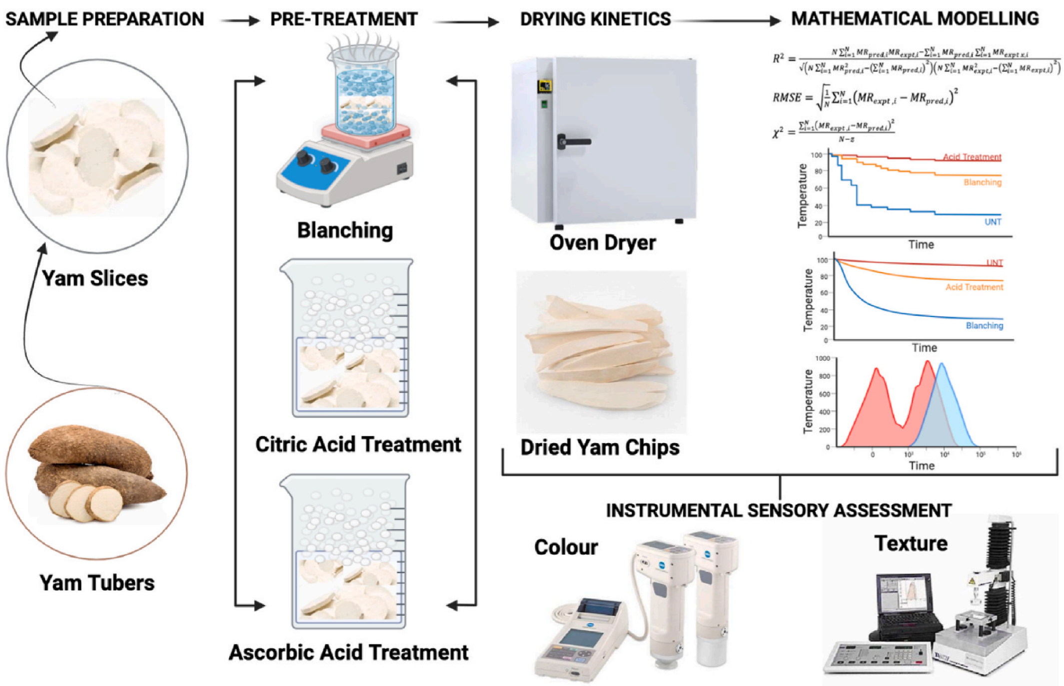
and sub-tropical regions (Africa, some Asia regions, the Pacific Island (Oceania), Central, and South America, and the Caribbean) for their stable dietary carbohydrate (energy) source [1]. The different types of yams include; yellow guinea yam (*Dioscorea cayenensis*), lesser yam (*Dioscorea esculenta*), greater or water yam (*Dioscorea alata*) and white yam (*Dioscorea rotundata*) [2]. Amankwah et al. [3] revealed that white yam (*Dioscorea rotundata*) tubers ('Pona', 'Dente', 'Lilii') are cylindrical and tapering in shape with rough scaly brown, firm exterior texture and white flesh. In Ghana, the 'Pona' variety is the most preferred and widely grown cultivar compared to the 'Dente' and 'Lilii' cultivars. Economically, yam rank fourth as the most integral root and tuber crop succeeding sweet potato, potato, and cassava globally and second after cassava in West Africa. Yam production generates income to greatly impact poverty alleviation and mitigate food insecurity and malnutrition issues in sub-Saharan Africa [4,5]. Yam (roots, tubers, and rhizomes) medicinal benefits coupled with pharmacological actions (antioxidant, antimicrobial, anticancer, immunomodulation, antiproliferative activities, etc.) are documented [3,4,6]. Yam is mostly consumed in diverse cooking forms (pounded, boiled, fried, or stewed) and transformed into yam flour [7]. Conversely, yam (*Dioscorea rotundata*) is predominantly produced in West Africa yet it is still under-exploited despite its economic, health therapies, and nutritional significance. To combat the highly underutilized status of yam classified as an orphan crop [2,4], processing yam into dried yam (yam chips) could meet consumer's demand for ready-to-eat food products thereby promoting yam consumption (see Scheme 1).

The use of pre-treatments is critical in the drying of food items. Pre-treatments aid to speed up the procedure of drying, improve food quality by enhancing colour, structure, and fragrance, and inhibit browning in dried food items [8]. Most agricultural products are pre-treated by thermal processing method blanching and also treated with chemicals like citric and ascorbic acids, sulphur, sodium hydroxide, sodium chloride, and calcium chloride before drying [9,10]. Wang et al. [11] reported that pre-treatment regimes and processing parameters greatly impact the food substrate (microstructural and catalyst actions) of dehydrated products. Blanching assists with microbial action reduction or destruction and removes moisture for shelf-life extension, maintains food quality for an increased consumer acceptance of the finished product, and inactivates enzymes that could cause quality degradation [12]. Blanching has been found to decrease the effect of browning and improve drying qualities in tubers [13,14]. Citric and ascorbic acid applications can soar the rate of drying, reduce food darkening, and enhance food quality of dried food products. Doymaz [15] demonstrated that the application of citric acid pre-treatments enhanced sweet potato slice's colour due to the acidic pH ability to control oxidation process and stabilizes the colour. Numerous experiments have been conducted on the drying properties of different food, and models have been suggested to expound the behaviour of the food product. As an energy intensive process, drying involves the application of latent heat to a product to evaporate the moisture. Analysis of energy consumption and thermodynamic properties during drying have become a great concern in the food and postharvest industries due to dryer types, dryer energy consumption, product energy requirements and cost of drying [16]. Convection dryers are very common in the industrial food drying and for drying all manner of food products [17]. The use of an effective drying system during drying is important in reducing energy cost and requirements and improving product quality after dehydration. In terms of energy efficiency, the performance of the drying system can be determined by the specific moisture extraction rate (SMER), the moisture extraction rate (MER), specific energy consumption (SEC) and total energy consumption rate (TECR). Several studies have been conducted on the drying properties of different food, energy consumption and



Scheme 1. Schematic illustration of pre-treatment and modelling on dried yam chips drying kinetics and instrumental sensory trait studies.

thermodynamic properties of drying systems and models have been suggested to explain the behaviour of the food product. The drying kinetics is essential for understanding the impact of dehydrating conditions, the energy effectiveness of evaporating systems, and how to preserve the trait of dried products [18]. However, there is a paucity of research on how temperature and pre-treatments affect the dehydrating dynamics, organoleptic characteristics, energy consumption, and thermodynamic properties of dried yam (*Dioscorea rotundata*) chips as a value-added-based convenient food product. Therefore, the study was aimed at investigating the synergistic impact of blanching and acid pre-treatments on dehydration kinetics and energy consumption via mathematical modelling and quality attribute of dehydrated yam chips.

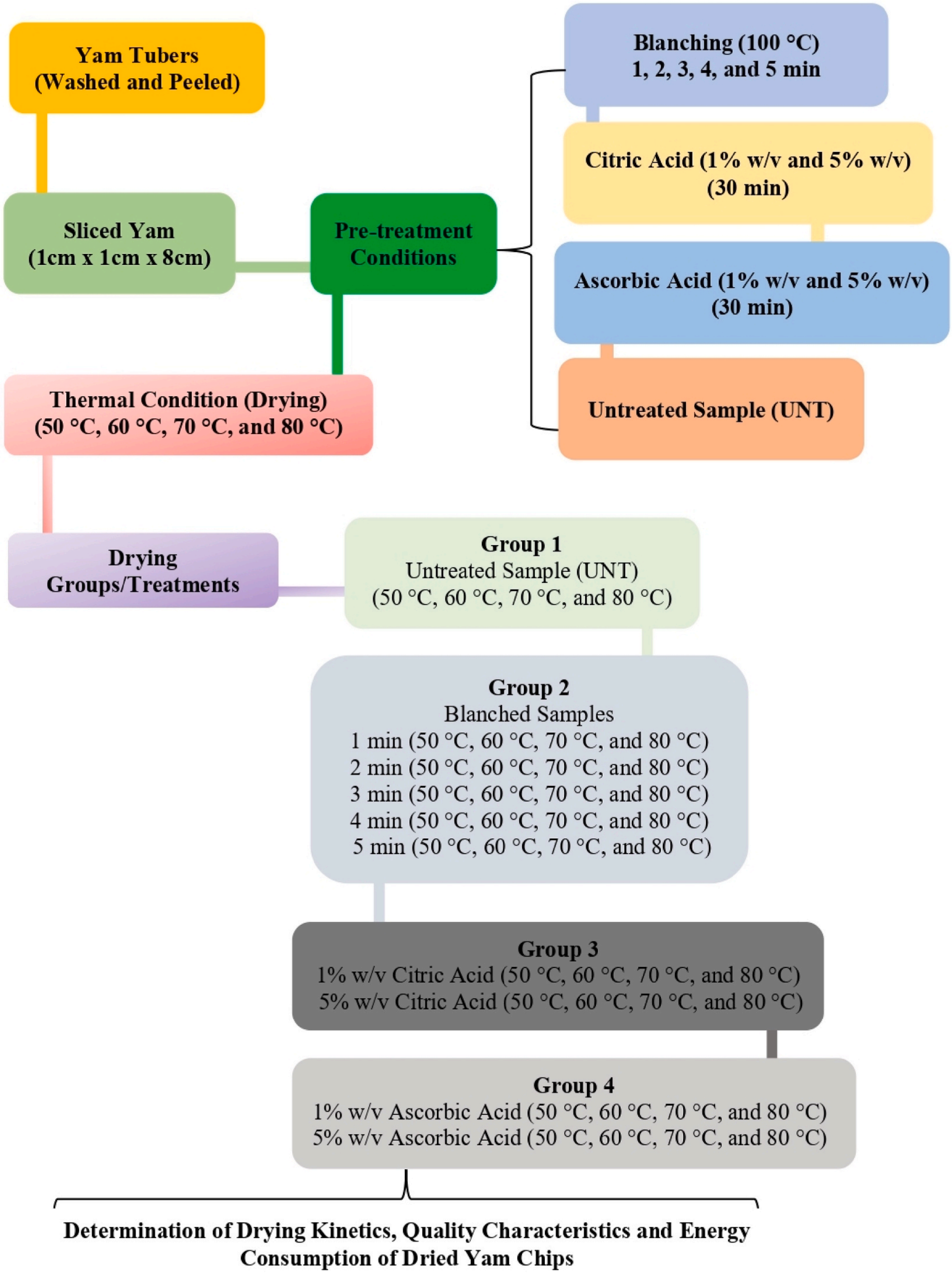


Fig. 1. Flow chart illustrating dried yam chips experimental technical route.

2. Materials and methods

2.1. Materials

The entire study was overseen in a pilot laboratory of the University of Energy and Natural Resources (Sunyani, Ghana) and the Council for Scientific and Industrial Research (CSIR) - Oil Palm Research Institute (OPRI) (Kade, Ghana). *Dioscorea rotundata* (Pona yam) variety was obtained from the open market in Ejura, Ashanti Region of Ghana located at 1°5′ W and 1°39′ W longitude and 7°9′ N and 7°36′ N latitudes. Chemicals and reagents employed in the study were supplied by the pilot plant and were of analytical standard.

2.2. Study design and preparation of sample

The flow chart (Fig. 1) illustrates the research technical route utilized for the study. Yam tubers were selected based on lack of physical defects, washed and cleansed with double distilled water to get rid of any inorganic materials. Afterwards, the yam was peeled manually adopting a stainless-steel kitchen knife and sliced (1 cm × 1 cm × 8 cm). The sliced yam samples were divided into four groups corresponding to thermal process and acidic solution pre-treatment conditions namely; control (untreated/unblanched samples: UNT group), thermal process blanched (1, 2, 3, 4, 5 min at 100 °C) group, citric acid group (1 % w/v or 5 % w/v for 30 min), and ascorbic acid group (1 % w/v or 5 % w/v for 30 min). Subsequently, the prepared pre-treated group samples (yam slices) were oven dried independently at 50 °C, 60 °C, 70 °C, and 80 °C, stored in a desiccator for drying kinetics analysis and further quality attributes analysis.

2.3. Pre-treatment of yam slices

2.3.1. Blanching of yam slices

Blanching was done by dipping 300 g of yam slices each in boiling water for 1 min, 2 min, 3 min, 4 min, and 5 min followed by a rapid cooling with running water to cease pre-treatment process. Blanched yam slices were drained and blotted with tissue paper before oven drying. Untreated or unblanched yam slices served as control samples.

2.3.2. Acid pre-treatment

Yam slices (300 g) each were separately submerged in 1 % w/v or 5 % w/v citric acid and ascorbic acid solution for 30 min. Following acid pre-treatment, yam samples were mopped up with paper tissue before oven drying.

2.4. Oven drying of pre-treated yam slices

A convectional oven dryer (SLN 75 POL-EKO-APPARATURA, Slaski, Poland) was the set-up utilized for dehydrating the pre-treated yam slices. Before loading samples, the oven system was left to rest (30 min) to establish a stable drying ambiance. Pre-treated yam slice's initial weight was determined and evenly spread on one-layer oven tray. The samples were dried independently at 50 °C, 60 °C, 70 °C, and 80 °C and air velocity of 2.0 m/s. The samples were taken out of the oven process every hour, cool to ambient temperature, and then weighed by applying a digital balance (PL2002, Mettler Toledo, Switzerland) to determine the drying characteristics. Three replicates of each measurement were determined. Drying continued until a constant weight was observed.

2.5. Drying quality

2.5.1. Moisture ratio

Lewis [19] employed the drying theory to explain the mass movement in thin layers of agricultural products during dehydration, based on Newton's rule of cooling in heat transmission. The moisture ratio (MR) of yam slices during the convective process was estimated using the Lewis theory, Bruce [20]; O'callaghan et al. [21], and Eqn. (1).

$$MR = \frac{M - M_e}{M_o - M_e} = exp(-kt) \tag{1}$$

M = moisture content at time t (g moisture/g dry matter), t = time (s), M_o = initial moisture content (g moisture/g dry matter), and M_e = equilibrium moisture content (g moisture/g dry matter), k = drying constant. Where MR = moisture ratio. To analyse dimensionless MR, M_e, was considered as zero [22,23].

2.6. Mathematical modelling of drying kinetics

The experimental set of (MR, t) drying kinetics of yam slices was fitted to three thin-layer drying models, which are frequently cited in the scientific literature shown in Table 1 to determine the suitable drying kinetics for the yam slices. The regression analysis was carried out utilizing Origin-Pro 9.2, (Origin Lab Corporation, Northampton, MA, USA). Three main variables: the coefficient of R^2; determination, RMSE; the root mean square error, and the Chi-square (reduced) were applied to assess the adaptation and quality of fit to the models (χ^2). R^2, RMSE, and χ^2 were determined with Eqns. (2)–(4), respectively.

$$R^2 = \frac{N\sum_{i=1}^{N} MR_{pred,i}MR_{expt,i} - \sum_{i=1}^{N} MR_{pred,i}\sum_{i=1}^{N} MR_{expt\ x,i}}{\sqrt{\left(N\sum_{i=1}^{N} MR_{pred,i}^2 - \left(\sum_{i=1}^{N} MR_{pred,i}\right)^2\right)\left(N\sum_{i=1}^{N} MR_{expt,i}^2 - \left(\sum_{i=1}^{N} MR_{expt,i}\right)^2\right)}} \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(MR_{expt,i} - MR_{pred,i}\right)^2} \quad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{expt,i} - MR_{pred,i}\right)^2}{N - z} \quad (4)$$

where N = the total number of observations, z = the total number of constants, and $MR_{expt,i}$ = experimentally determined dimensionless *MR*, $MR_{pred,i}$ = anticipated determined dimensionless *MR*. The model with the highest R^2 and the least RMSE and χ^2 values were chosen to reflect the best drying dynamics of yam slices at various temperatures [24].

2.7. Determination of physical properties of dried yam chips

2.7.1. Texture profile analysis

The texture analyser type TA-XT Plus with a 2-mm cylindrical probe (Stable Micro Systems Ltd., Surrey, England, U.K.) in compressive form was used to assess the texture qualities of dried yam chips. The oven-dried yam chips sample was deposited on the test board, crossed by the probe's flat end as it descended vertically to fracture at an assessment speed of 1 mm s^{-1}. The greatest coercion in the force-deformation curve was used to define hardness [25]. Each sample obtained from a variety of drying settings underwent twenty measurements.

2.7.2. Colour measurement

The colour of the yam chip's external surface was evaluated by applying a Minolta portable Chroma meter (Minolta Co. Ltd., Model CR 310, Japan) with illuminant (D65), viewing angle (0°), and viewing area diameter (0.12 mm). Samples were left to reach ambient temperature after being taken out from the oven. Before colour measurement, the colorimeter was calibrated by employing a white tile as the standard. L^*, which spans from darkness–0 to lightness–100 in the Hunter Lab's colour radiance coordinates, estimates a colour's lightness index. The chromaticity coordinates, a^* measured red when positive and green when negative. Whereas, b^* assessed yellow when positive and blue when negative [26]. According to Sarpong et al. [23], the criterion for L^*, a^*, and b^* were determined using the total colour difference (E) formulae (Eqn. (5)).

$$\Delta E* = \sqrt{\left(L_0^* - L^*\right)^2 + \left(a_0^* - a^*\right)^2 + \left(b_0^* - b^*\right)^2} \quad (5)$$

where: $L_0^* - L^*$ = initial and final lightness, $a_0^* - a^*$ = initial and final redness, $b_0^* - b^*$ = initial and final yellowness.

2.8. Energy consumption parameters

2.8.1. Effective moisture diffusivity (D_{eff})

During the decreasing rate period of drying, Fick's second rule of diffusion was employed to describe the drying process (regulated by internal diffusion) and is illustrated in Eqn. (6)

$$\frac{\partial M}{\partial t} = D_{eff}\nabla^2 M \quad (6)$$

On the basis of the assumptions of continuous diffusivity, unidimensional moisture flow, volume change, constant temperature, and minimal external resistance, the diffusivity, D_{eff} (m^2/s) equation was calculated for slab shape [27]. The formula is shown in Eqn. (7).

Table 1
Mathematical models adopted to simulate yam slices dehydrating process.

Model name	Model	Reference(s)
Lewis	$MR = exp(-kt)$	[20] [19] [21]
Page	$MR = exp(-kt^n)$	[42] [44] [43]
Asymptotic	$MR = a - b \times c\ exp(t)$	[46]

$$MR = \frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}exp\left[-\frac{(2n-1)^2\pi^2 D_{eff}\, t}{4L^2}\right] \quad (7)$$

where L and t represent one-half of the slice thickness and drying time, respectively, and D_{eff} is a constant effective diffusion coefficient (m^2/s). For lengthy drying times, only the first terms of Eqn (3) can be employed;

$$MR = \frac{M_t}{M_0} = \frac{8}{\pi^2}exp\left(-\frac{\pi^2 D_{eff}\ t}{4L^2}\right) \quad (8)$$

D_{eff} is commonly estimated by graphing the experimental moisture ratio against the drying time in logarithmic manner.

$$k_0 = \frac{\pi^2 D_{eff}}{4L^2} \quad (9)$$

2.8.2. Energy efficiency of the drying system

A power measurement tool was used to gauge the convective process' energy usage. Equations (10)–(13) were used to compute the specific moisture extraction rate (SMER), the moisture extraction rate (MER), the specific energy consumption (SEC), and the total energy consumption (E_t), respectively, in order to assess the efficiency of drier systems.

$$\text{SMER} = \frac{\textit{Amount of water removed during drying}\ (kg)}{\textit{Total energy supplied in drying process}\ (KWh)} \quad (10)$$

$$\text{MER} = \frac{\textit{Amount of water removed during drying}\ (Kg)}{\textit{Drying time}} \quad (11)$$

$$\text{SEC} = \frac{\textit{Total energy supplied in drying process}\ (KWh)}{\textit{Amount of water removed during drying}\ (Kg)} \quad (12)$$

$$\text{Total energy consumed}\ (E_t) = \text{Voltage(V)} \times \text{Current(I)} \times \text{Time(hr)}, (\text{kWh}) \quad (13)$$

2.9. Thermodynamic properties of yam chips

2.9.1. Activation energy (E_a)

Temperature frequently affects the rate constant. As a result, the temperature dependency of drying kinetics was estimated using Arrhenius Eqn. (14).

$$\boldsymbol{In}\ (\boldsymbol{k}) = \boldsymbol{In}\ (\boldsymbol{C}) - \frac{\boldsymbol{E_a}}{\boldsymbol{RT}} \quad (14)$$

where R is the universal gas constant (8.314 J/mol K), T is the temperature (K), E_a is the activation energy (kJ/mol), and C is the Arrhenius constant.

Using Arrhenius Eqn. (14), activation energy (*Ea*, kJ/mol) was calculated. The Gibbs free energy change (Δ G), the enthalpy change (Δ H), and the entropy change (Δ S) were calculated using the activation energy and rate constant of the process … Eqn. 15–17

$$\Delta G = R * T * In\left(\frac{k * h_P}{T * K_B}\right) \quad (15)$$

$$\Delta H = E_a - RT \quad (16)$$

$$\Delta S = \left(\frac{\Delta H - \Delta G}{T}\right) \quad (17)$$

where K_B the Boltzmann's constant (1.3806×10^{-23} J/K) and h_p is the Planck constant (6.6262×10^{-34} J s).

2.10. Statistical analysis

Data from the studies were statistically examined using Origin-Pro 9.2 (Origin Lab Corporation, Northampton, MA, USA) and all experiments were replicated. One-way ANOVA and Fishers' comparison tests were used to identify the level of significance ($p < 0.05$) and values of data were expressed as mean ± standard deviations.

3. Results and discussions

3.1. Drying kinetics

3.1.1. Effect of blanching pre-treatment on weight loss of yam chips during oven drying

The drying curve in Fig. 2 presents information about the disparity of water content relative to the dehydration time of the blanched dried yam chips. It was observed that the entire drying time was decreased with a surge in drying temperature. Samples took 26 h at 50 °C, 23–24 h at 60 °C, 20–21 h at 70 °C, and 14–15 h at 80 °C to dry completely. The dried products final moisture contents ranged between 23.59 and 40.51 %, 20.15–26.81 %, 19.34–21.12 %, and 12.45–20.35 % which corresponded to 50 °C, 60 °C, 70 °C, and 80 °C respectively. The outcomes show that drying occurred more quickly at surging temperatures than at low temperatures, as shown by the curves. According to Singh et al. [8], the studies on the drying process for food products (button mushroom slices) were reported to follow a predictable pattern. In the current investigation, it was established that the drying curves' constant rate period was absent and that drying occurred among all the samples during the falling rate period. Hence, this could be ascribed to the swift withdrawal of water since there was no free water at the sample's exterior before dehydration. Additionally, the results suggest that diffusion was probably the physical process that controlled the inner mass transfer of the yam chips during the drying process, thereby, causing the migration of water from the inside (wet) zone to the outer where it becomes waterless [28]. The outcomes of the study corroborated with research findings for diced cassava root [29], cassava chips [30], organic tomato [31], and carrot [32]. In Fig. 2, the effective drying rates of blanched yam chips at 80 °C demonstrates how high temperatures increased the permeability of the yam slices' cell membranes, which increased the water diffusivity and decreased drying time. Comparatively, among all the pre-treated blanched and unblanched samples, UNT chips at 50 °C lost more weight compared to 1 min blanched chips (163.47 g), 4 min blanched chips (163.42 g), and 5 min blanched chips (159.49 g) dried at 50 °C. Also, at 60 °C, UNT samples experienced more weight loss (174.93 g) compared to 1 min blanched chips at 60 °C (173.19 g). Invariably, the noticed phenomena might be caused by the pre-treatment condition of blanching which made the product more resistant to moisture loss during drying, and to an extent would increase drying time as reported by Dinrifo [33]. Furthermore, the yam chips' increased level of starch gelatinization during the thermal process may have prevented moisture from evaporating from the interior of the yam chips matrix to its exterior amid drying. In a similar investigation by Mate et al. [34], blanching potatoes slowed drying because starch gelatinization reduced porosity. Likewise, the findings of the study agree with Falade et al. [35] on air-drying and rehydration properties of date palm (*Phoenix dactylifera* L.) fruits.

3.1.2. Impact of acid pre-treatments on weight loss of yam chips during oven drying

Varying concentrations of citric and ascorbic acids on mass loss of the dehydrated yam chips at various temperatures were studied (Fig. 3). The final moisture contents in citric pre-treated samples ranged between 23.23 and 25.22 %, 20.21–21.44 %, 19.11–19.20 %,

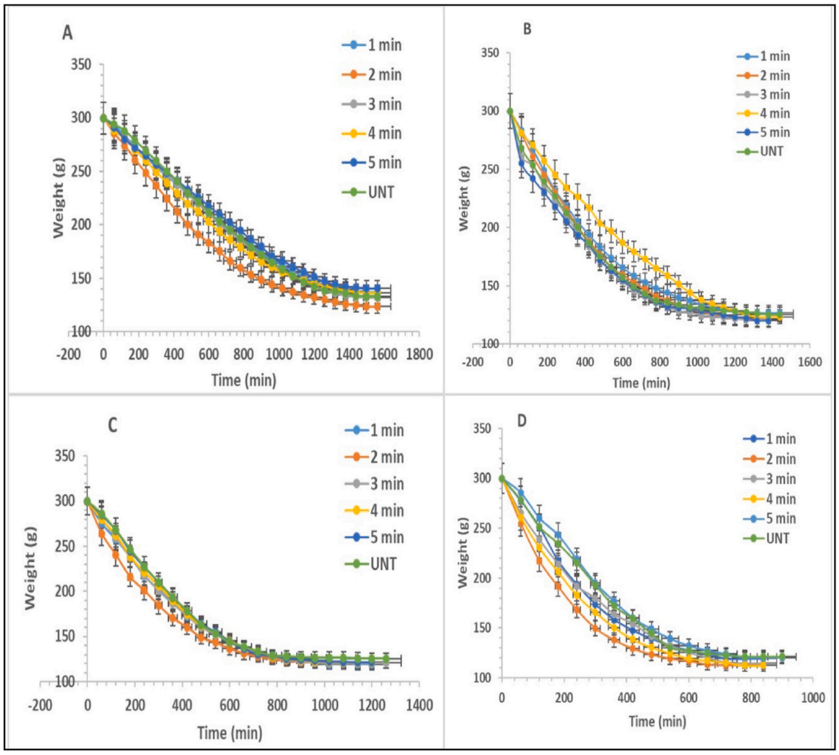


Fig. 2. Effect of blanching time and temperature (A: 50 °C, B: 60 °C, C: 70 °C, and D: 80 °C) on weight loss during oven drying of yam chips.

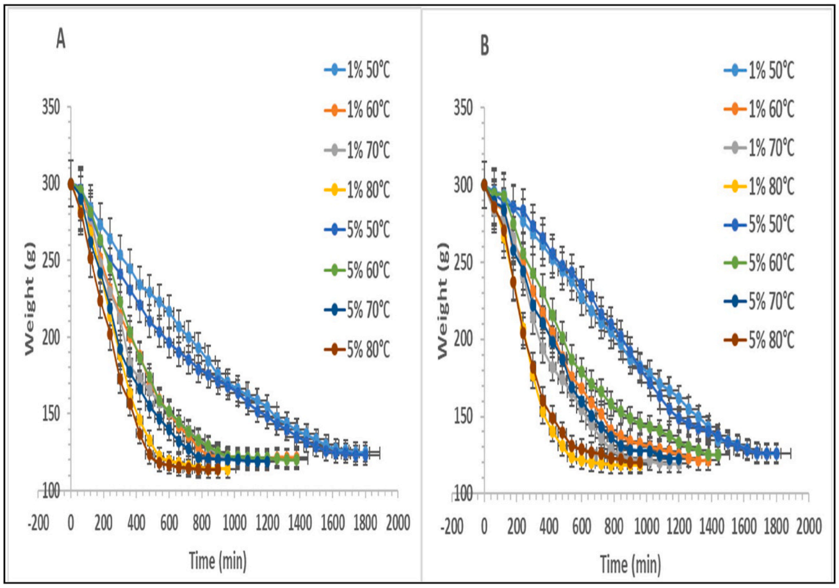


Fig. 3. Effect of temperature and acid treatments (A: citric acid; B: ascorbic acid) on weight loss during oven drying of yam chips.

and 13.73–14.21 % for 50 °C, 60 °C, 70 °C, and 80 °C respectively. Whereas, in the ascorbic pre-treated samples the moisture composition ranged between 25.71 and 26.36 %, 21.65–25.45 %, 19.65–22.77 %, and 18.38–20.21 % corresponded to 50 °C, 60 °C, 70 °C, and 80 °C temperatures respectively. In comparison to the UNT results in Fig. 2, UNT samples dried at 50 °C took 1560 min (26 h) to reach equilibrium moisture content with a weight loss of 167.02 g. At 60 °C, 70 °C, and 80 °C equilibrium levels were reached after 1440 min (24 h), 1260 min (21 h), and 900 (15 h) min respectively of drying corresponding with weight losses of 174.93 g, 174.58 g, and 178.55 g. Therefore, final moisture contents of 32.98 %, 25.07 %, 25.42 %, and 21.45 % corresponding to 50 °C, 60 °C, 70 °C, and 80 °C were observed. These findings demonstrate that the administration of citric and ascorbic acid disrupted structures of the yam sample to increase the permeability of the yam chips' cell membranes, which increased diffusivity (D_{eff}). The pre-treatment leaching effects, which changed the tissues of the chips and made it simpler for water to permeate through during drying, may relate to the increased moisture losses in the dried products. According to a study by Fuente-Blanco et al. [36], acid pre-treatment application on fruits softens the tissues thereby making it possible for water to pass through easily. Related findings have also been noted in the drying of bananas [37]. Also, the variation in the different drying temperatures influenced dehydration. At an excessive temperature of 80 °C, moisture removal in the yam slices was quicker compared to the lower temperatures leading to less drying time. The outcome corroborates with complementary findings reported in the dehydration of garlic slices [38], onion slices [39], and eggplants [40].

3.1.3. Drying curves fitting

To design and operate dryers, drying models are employed to estimate water composition and dehydrating time under specific drying techniques, enhance drying functionalities, and generalize drying dynamics [41]. The test results for the different pre-treatments were well-fitted to the models employed in this work (Tables 2–4). All three models (Lewis, Page, and Asymptotic) utilized consistently produced R^2 values between 0.839 and 0.999, suggesting the suitability of using the models to explain the drying manner of yam chips in the process of a variety of pre-treatments (blanching, citric, and ascorbic acids) and various drying set-up (50, 60, 70, and 80 °C). However, the asymptotic model, which had the greatest R^2 value (0.999), lowest χ^2 (4.422), and lowest RMSE (2.103) for blanching pre-treatments at 80 °C, was discovered to be the best descriptive model. According to Tables 2 and 3, the asymptotic model had the highest R^2 value (0.998), the lowest χ^2 value (7.134), and the least RMSE value (2.670) for citric acid pre-treatment at 50 °C. Equally for ascorbic acid pre-treatment at 50 °C, R^2 had 0.995 as the highest value, 18.498 as χ^2 lowest value, and the lowest RMSE value (4.301). The Asymptotic model is more appropriate to represent the description of water in yam chips with the temperature examined compared to the Lewis model [21] and Page model, according to the relatively higher R^2 values, lower χ^2 and RMSE values [42–44]. In a like manner, this model has been utilized to precisely simulate and forecast the dehydration of coffee beans and onion slices [45,46].

3.2. Effect of pre-treatments on texture and colour of yam chips

Important quality factors that influence consumers' propensity to acceptance and market value of a food product include texture which plays an integral role in food sensory evaluation and colour. Both postharvest and the food sector utilize instrumental sensory analysis metrics to assess the trait of dried food products.

Table 2
The coefficients of the tested models on blanching pre-treatment and untreated (UNT) samples at different drying time and temperatures.

Treatments	Time (min)	Model Name	Temp. (°C)	Constants			R^2	χ^2	RMSE
Blanching	1	Lewis	50	$k = -5.607 \times 10^{-4}$			0.985	0.001	0.033
			60	$k = -6.122 \times 10^{-4}$			0.916	0.007	0.084
			70	$k = -7.972 \times 10^{-4}$			0.908	0.009	0.097
			80	$k = -0.001$			0.921	0.009	0.095
		Page	50	$k = -1.064 \times 10^{-4}$			0.988	3.33×10^{-05}	0.060
			60	$k = -1.180 \times 10^{-4}$			0.925	2.28×10^{-04}	0.015
			70	$k = -1.548 \times 10^{-4}$			0.916	3.17×10^{-04}	0.018
			80	$k = -2.240 \times 10^{-4}$			0.930	2.92×10^{-04}	0.017
		Asymptotic	50	a = 63.193	b = −243.440	c = 0.999	0.995	14.406	3.795
			60	a = 112.828	b = −193.535	c = 0.998	0.998	7.316	2.704
			70	a = 103.058	b = −202.821	c = 0.997	0.995	17.426	4.174
			80	a = 101.041	b = −208.524	c = 0.997	0.993	30.190	5.494
Blanching	2	Lewis	50	$k = -6.001 \times 10^{-4}$			0.954	0.004	0.060
			60	$k = -6.703 \times 10^{-4}$			0.922	0.007	0.084
			70	$k = -7.201 \times 10^{-4}$			0.854	0.013	0.114
			80	$k = -0.001$			0.855	0.016	0.128
		Page	50	$k = -1.155 \times 10^{-4}$			0.961	1.28×10^{-04}	0.011
			60	$k = -1.298 \times 10^{-4}$			0.932	2.33×10^{-04}	0.015
			70	$k = -1.403 \times 10^{-4}$			0.866	4.46×10^{-04}	0.022
			80	$k = -2.193 \times 10^{-4}$			0.868	5.67×10^{-04}	0.024
		Asymptotic	50	a = 98.121	b = −208.566	c = 0.999	0.997	11.565	3.401
			60	a = 106.520	b = −198.640	c = 0.998	0.997	8.551	2.924
			70	a = 113.835	b = −186.819	c = 0.997	0.998	4.875	2.208
			80	a = 106.186	b = −196.351	c = 0.995	0.999	4.986	2.233
Blanching	3	Lewis	50	$k = -5.855 \times 10^{-4}$			0.986	0.00109	0.032
			60	$k = -6.540 \times 10^{-4}$			0.903	0.008	0.092
			70	$k = -7.443 \times 10^{-4}$			0.883	0.012	0.108
			80	$k = -0.001$			0.954	0.006	0.072
		Page	50	$k = -1.115 \times 10^{-4}$			0.989	1.46×10^{-05}	0.006
			60	$k = -1.272 \times 10^{-4}$			0.912	2.84×10^{-04}	0.017
			70	$k = -1.445 \times 10^{-4}$			0.893	3.99×10^{-04}	0.020
			80	$k = -2.281 \times 10^{-4}$			0.962	1.58×10^{-04}	0.013
		Asymptotic	50	a = 47.449	b = −258.692	c = 0.999	0.994	18.696	4.323
			60	a = 107.175	b = −190.285	c = 0.997	0.994	20.102	4.484
			70	a = 107.326	b = −201.688	c = 0.997	0.994	20.314	4.507
			80	a = 94.542	b = −205.680	c = 0.997	0.999	4.422	2.103
Blanching	4	Lewis	50	$k = -5.496 \times 10^{-4}$			0.972	0.002	0.045
			60	$k = -6.577 \times 10^{-4}$			0.982	0.001	0.032
			70	$k = -7.959 \times 10^{-4}$			0.904	0.010	0.099
			80	$k = -0.001$			0.913	0.010	0.100
		Page	50	$k = -1.045 \times 10^{-4}$			0.976	6.50×10^{-05}	0.008
			60	$k = -1.266 \times 10^{-4}$			0.986	3.49×10^{-04}	0.005
			70	$k = -1.542 \times 10^{-4}$			0.912	3.33×10^{-04}	0.018
			80	$k = -2.282 \times 10^{-4}$			0.924	3.33×10^{-04}	0.018
		Asymptotic	50	a = 92.479	b = −214.165	c = 0.999	0.995	14.861	3.855
			60	a = 73.744	b = −226.568	c = 0.998	0.997	8.575	2.928
			70	a = 103.599	b = −204.886	c = 0.998	0.993	25.248	5.025
			80	a = 100.760	b = −201.346	c = 0.996	0.999	5.622	2.371
Blanching	5	Lewis	50	$k = -5.387 \times 10^{-4}$			0.988	0.001	0.030
			60	$k = -6.247 \times 10^{-4}$			0.910	0.006	0.075
			70	$k = -8.010 \times 10^{-4}$			0.901	0.010	0.102
			80	$k = -0.001$			0.943	0.007	0.082
		Page	50	$k = -1.019 \times 10^{-4}$			0.988	2.77×10^{-05}	0.006
			60	$k = -1.215 \times 10^{-4}$			0.920	1.78×10^{-04}	0.013
			70	$k = -1.567 \times 10^{-4}$			0.909	3.57×10^{-04}	0.019
			80	$k = -2.174 \times 10^{-4}$			0.950	2.20×10^{-04}	0.015
		Asymptotic	50	a = 46.938	b = −257.035	c = 0.999	0.994	16.672	4.083
			60	a = 110.566	b = −180.443	c = 0.998	0.993	20.123	4.486
			70	a = 101.580	b = −210.592	c = 0.998	0.989	42.370	6.509
			80	a = 86.134	b = −226.017	c = 0.998	0.988	53.937	7.344
Untreated (UNT)		Lewis	50	$k = -5.936 \times 10^{-4}$			0.984	0.001	0.037
			60	$k = -5.934 \times 10^{-4}$			0.881	0.007	0.081
			70	$k = -7.324 \times 10^{-4}$			0.863	0.014	0.117
			80	$k = -0.0011$			0.923	0.009	0.094
		Page	50	$k = -1.128 \times 10^{-4}$			0.986	4.29×10^{-05}	0.007
			60	$k = -1.148 \times 10^{-4}$			0.890	2.18×10^{-04}	0.015
			70	$k = -1.413 \times 10^{-4}$			0.871	4.72×10^{-04}	0.022
			80	$k = -2.131 \times 10^{-4}$			0.928	3.06×10^{-04}	0.017

(continued on next page)

Table 2 (*continued*)

Treatments	Time (min)	Model Name	Temp. (°C)	Constants			R^2	χ^2	RMSE
		Asymptotic	50	a = 46.644	b = −264.041	c = 0.999	0.992	26.708	5.168
			60	a = 114.572	b = −185.809	c = 0.998	0.994	18.004	4.243
			70	a = 109.728	b = −204.519	c = 0.997	0.986	53.759	7.332
			80	a = 92.379	b = −216.309	c = 0.997	0.987	55.435	7.445

R^2: regression coefficient; Temp: temperature (°C); χ^2: quality of fit to the models; RMSE: root means square error.

Table 3
Curve fitting criteria for mathematical models and parameters at different citric acid concentrations and drying temperatures.

Treatment	Conc. (%)	Model Name	Temp. (°C)	Constants			R^2	χ^2	RMSE
Citric acid	1 %	Lewis	50	$k = -5.240 \times 10^{-4}$			0.990	0.001	0.030
			60	$k = -7.299 \times 10^{-4}$			0.881	0.013	0.116
			70	$k = -7.299 \times 10^{-4}$			0.882	0.013	0.116
			80	k = −0.001			0.881	0.017	0.130
		Page	50	$k = -1.003 \times 10^{-4}$			0.992	2.23×10^{-05}	0.005
			60	$k = -1.411 \times 10^{-4}$			0.886	4.60×10^{-04}	0.021
			70	$K = -1.569 \times 10^{-4}$			0.881	4.87×10^{-04}	0.022
			80	$k = -2.188 \times 10^{-4}$			0.888	5.93×10^{-04}	0.024
		Asymptotic	50	a = 63.649	b = −242.389	c = 0.999	0.998	7.134	2.670
			60	a = 100.771	b = −220.892	c = 0.998	0.980	81.971	9.054
			70	a = 105.318	b = −210.080	c = 0.997	0.989	45.118	6.717
			80	a = 88.477	b = −229.719	c = 0.997	0.973	137.346	11.720
	5 %	Lewis	50	$k = -5.102 \times 10^{-4}$			0.977	0.002	0.043
			60	$k = -7.097 \times 10^{-4}$			0.865	0.014	0.121
			70	$k = -8.223 \times 10^{-4}$			0.923	0.018	0.906
			80	k = −0.001			0.875	0.017	0.169
		Page	50	$k = -9.817 \times 10^{-4}$			0.983	5.07×10^{-05}	0.007
			60	$K = -1.375 \times 10^{-4}$			0.873	5.16×10^{-04}	0.023
			70	$K = -1.591 \times 10^{-4}$			0.993	2.65×10^{-04}	0.016
			80	$k = -2.284 \times 10^{-4}$			0.882	6.10×10^{-04}	0.025
		Asymptotic	50	a = 95.370	b = −207.831	c = 0.999	0.995	8.226	2.869
			60	a = 103.988	b = −213.662	c = 0.998	0.985	58.729	7.663
			70	a = 100.029	b = −213.343	c = 0.998	0.988	45.849	6.771
			80	a = 92.837	b = −221.431	c = 0.997	0.981	91.134	9.546

R^2: regression coefficient; Conc.: concentration (%); Temp.: temperature (°C); χ^2: quality of fit to the models; RMSE: root means square error.

Table 4
Curve fitting criteria for mathematical models and parameters at different ascorbic acid concentrations and drying temperatures.

Treatment	Conc. (%)	Model Name	Temp. (°C)	Constants			R^2	χ^2	RMSE
Ascorbic acid	1 %	Lewis	50	$k = 5.439 \times 10^{-4}$			0.994	5.72×10^{-04}	0.024
			60	$k = -7.154 \times 10^{-4}$			0.934	6.82×10^{-03}	0.083
			70	$k = -8.522 \times 10^{-4}$			0.931	7.84×10^{-03}	0.885
			80	k = −0.001			0.839	0.021	0.144
		Page	50	$k = -1.037 \times 10^{-4}$			0.994	3.30×10^{-05}	0.006
			60	$k = -1.378 \times 10^{-4}$			0.941	2.23×10^{-04}	0.015
			70	$k = -1.647 \times 10^{-4}$			0.938	4.25×10^{-04}	0.016
			80	$k = -2.042 \times 10^{-4}$			0.848	7.33×10^{-04}	0.027
		Asymptotic	50	a = −12.111	b = −322.879	c = 0.999	0.995	18.498	4.301
			60	a = 94.871	b = −219.944	c = 0.998	0.988	47.509	6.893
			70	a = 89.830	b = −224.444	c = 0.998	0.984	70.701	8.408
			80	a = 99.737	b = −220.952	c = 0.997	0.969	151.472	12.307
	5 %	Lewis	50	$k = -5.623 \times 10^{-4}$			0.981	1.87	0.043
			60	$k = -6.594 \times 10^{-4}$			0.954	0.004	0.065
			70	$k = -8.325 \times 10^{-4}$			0.947	0.006	0.075
			80	k = −0.001			0.872	0.015	0.123
		Page	50	$k = -1.071 \times 10^{-4}$			0.981	1.74×10^{-05}	0.008
			60	$k = -1.261 \times 10^{-4}$			0.961	1.29×10^{-04}	0.011
			70	$k = -1.601 \times 10^{-4}$			0.953	3.79×10^{-04}	0.014
			80	$k = -1.974 \times 10^{-4}$			0.881	5.94×10^{-04}	0.023
		Asymptotic	50	a = −38.053	b = −351.334	c = 0.999	0.984	62.849	7.928
			60	a = 95.905	b = −221.214	c = 0.998	0.988	43.762	6.615
			70	a = 86.309	b = −227.906	c = 0.998	0.987	52.134	7.220
			80	a = 102.982	b = −215.129	c = 0.997	0.976	108.122	10.398

R^2: regression coefficient; Conc.: concentration (%); Temp.: temperature (°C); χ^2: quality of fit to the models; RMSE: root means square error.

3.2.1. Texture

The impact of pre-treatments and dehydration conditions on the hardness of dehydrated yam chips are shown in Tables 5–7. Results indicate that yam chips blanched for 1 and 3 min were significantly ($p < 0.05$) impacted and had 74 N and 78 N of hardness values, respectively, at 50 °C. Except for yam chips blanched for 5 min, all blanched yam chips greatly outperformed untreated chips in terms of hardness at a temperature of 60 °C. Yam chips that were blanched for 2 min and then dried at 70 °C had harder surfaces (73 N) compared to the UNT chips (64.5 N). The hardest yam chips were samples subjected to blanching for 4 min at 80 °C temperature, significantly ($p < 0.05$) higher (81.3 N) than any other times (min) or temperatures (°C). According to Table 6, yam chips immersed in 5 % citric acid at 80 °C had the surged hardness value (79.5 N), come after 1 % at 50 °C (73.3 N), and 5 % at 50 °C had the lowest hardness value (55.5 N). In Table 7, yam chips that had been submerged in 1 % ascorbic acid at 80 °C temperature produced the highest hardness value of 78.0 N. The findings show that temperature had a substantial impact on the pre-treated yam chips' hardness characteristic. The outcome is consistent with related findings by Sanful [47], who found that raising the dehydration temperature influenced the quick removal of moisture and subsequent reduction in the porosity of the chips, resulting in a harder texture. According to Pedreschi et al. [48], product hardness depends on the quantity of water lost or removed and the level of crust formation. The higher harder value of the blanched samples mechanism could be a result of significant structural changes during heat treatment leading to denser and more compact structures. In contrast, citric and ascorbic acid pre-treatments may to an extent induce the same level of structural changes based on their comparatively inconsistent hardness values at the different drying temperatures in the dried yam chips.

3.2.2. Colour

Findings of colour assessments for the dried yam chips are presented in Tables 5–7. At 80 °C of drying, 5 % citric acid had 69.6, 3.53, 15.16, 1 % ascorbic acid had 62.28, 0.38, 6.57, and blanching at 4 min had 71.07, 0.60, 16.21 of L^*, a^*, and b^* values respectively. The results show that temperature and pre-treatments had a substantial ($p < 0.05$) impact on the L^*, a^*, and b^* colour indices after drying. The findings revealed a decline in the dried yam chips' lightness (L^*) values compared to the initial data. Customers may become less interested in a particular product as a result of colour changes that can occur during the dehydration process for food products [49,50]. As opposed to drying yam chips via oven thermal technique at 70, 60, and 50 °C, which produced darker-coloured chips, conversely, drying at 80 °C resulted in whiter chips. Moisture affects the colour of food products by inducing the Maillard reaction, an enzymatic browning or darkening [49–51]. The samples are quickly dried out at higher temperatures, which prevents enzymatic browning and results in the lightest products [52]. In comparison to the UNT value of 0.43 and −0.64, the redness (a^*) index of yam chips was determined to be the maximum and minimum. Redness for samples that had been blanched peaked at 0.60 ± 0.03 at 4 min, 80 °C and at 3 min, 50 °C peaked −0.04 ± 0.01 (Table 5). Table 6 shows that for citric acid, the highest redness value was at 5 % concentration at 80 °C (3.53 ± 0.29), and the least value was −0.24 ± 0.01 at 5 %, 60 °C. For ascorbic acid pre-treated samples, there was a simple rise in the redness value, with the greatest value of 6.39 ± 0.07 obtained at 1 %, 80 °C from Table 7.

The findings are consistent with experimental findings by Odenigbo et al. [53] that increasing redness indicates surged crust

Table 5
Effect of drying temperature and blanching time on texture and colour of dehydrated yam chips.

Temperature (°C)	Time (mins)	Texture	Colour		
		Hardness (N)	L^*	a^*	b^*
50	UNT	67.00 ± 3.34^{b}	60.78 ± 0.75^{b}	0.43 ± 0.02^{d}	9.06 ± 0.17^{a}
	1	74.00 ± 2.56^{c}	63.28 ± 1.16^{b}	0.21 ± 0.01^{cd}	14.07 ± 0.29^{de}
	2	65.00 ± 2.88^{b}	64.72 ± 1.5^{bc}	0.10 ± 0.01^{c}	11.34 ± 0.91^{b}
	3	78.00 ± 3.43^{c}	57.89 ± 0.34^{ab}	−0.04 ± 0.01^{b}	14.84 ± 1.4^{e}
	4	66.00 ± 2.37^{b}	62.70 ± 2.16^{b}	0.19 ± 0.01^{c}	14.55 ± 1.31^{e}
	5	55.50 ± 2.54^{a}	62.34 ± 1.11^{b}	−0.14 ± 0.01^{b}	13.47 ± 0.58^{d}
60	UNT	66.50 ± 2.65^{b}	62.27 ± 1.0^{b}	−0.64 ± 0.02^{b}	8.95 ± 0.07^{a}
	1	71.50 ± 2.45^{c}	64.5 ± 2.16^{bc}	−0.56 ± 0.04^{b}	11.7 ± 0.49^{b}
	2	71.00 ± 3.34^{c}	60.56 ± 1.78^{b}	−1.14 ± 0.04^{a}	12.3 ± 0.21^{c}
	3	74.50 ± 3.34^{c}	57.61 ± 1.95^{a}	−0.81 ± 0.02^{b}	12.62 ± 1.17^{c}
	4	75.50 ± 4.23^{c}	65.34 ± 3.00^{c}	−1.36 ± 0.05^{a}	13.39 ± 0.84^{d}
	5	64.00 ± 2.33^{b}	60.3 ± 1.26^{b}	−1.44 ± 0.03^{a}	14.57 ± 0.44^{e}
70	UNT	64.50 ± 2.45^{b}	61.88 ± 1.57^{b}	−0.13 ± 0.12^{b}	14.23 ± 0.45^{e}
	1	64.00 ± 3.50^{b}	57.06 ± 2.72^{a}	−0.34 ± 0.01^{b}	12.47 ± 0.82^{c}
	2	73.00 ± 3.21^{c}	62.56 ± 2.10^{b}	0.35 ± 0.01^{d}	10.9 ± 0.60^{a}
	3	66.00 ± 3.45^{b}	64.35 ± 2.21^{b}	−0.13 ± 0.04^{b}	12.66 ± 0.44^{c}
	4	69.50 ± 2.76^{bc}	53.72 ± 3.06^{a}	−0.71 ± 0.01^{b}	13.38 ± 1.05^{d}
	5	68.50 ± 3.45^{bc}	60.68 ± 2.99^{b}	−0.80 ± 0.02^{b}	12.85 ± 0.17^{c}
80	UNT	64.50 ± 3.24^{b}	60.66 ± 2.89^{b}	−0.46 ± 0.04^{b}	8.58 ± 0.24^{a}
	1	53.50 ± 3.35^{a}	65.72 ± 2.65^{c}	−0.85 ± 0.02^{b}	13.52 ± 0.97^{d}
	2	73.50 ± 3.12^{c}	65.32 ± 1.13^{c}	−0.91 ± 0.02^{b}	11.55 ± 1.12^{b}
	3	65.00 ± 2.87^{b}	64.78 ± 1.55^{bc}	−0.33 ± 0.03^{b}	10.43 ± 0.53^{a}
	4	81.30 ± 2.34^{d}	71.07 ± 0.49^{d}	0.60 ± 0.03^{e}	16.21 ± 0.23^{f}
	5	52.00 ± 2.45^{a}	64.67 ± 1.95^{b}	0.22 ± 0.02^{d}	11.48 ± 1.04^{b}

Values are means ± standard deviation ($n = 3$); Different letters in the same column indicate significant differences ($P < 0.05$) using Tukey's HSD (honestly significant difference) test. UNT: untreated yam slices sample; L^*: lightness; a^*: redness; b^*: yellowness.

Table 6
Effect of citric acid pre-treatment and drying temperature on texture and colour of dehydrated yam chips.

Citric acid concentration (%)	Drying Temperature (°C)	Texture	Colour		
		Hardness (N)	*L**	*a**	*b**
1	50	73.5 ± 3.12^{e}	64.01 ± 1.66^{b}	−0.46 ± 0.04^{c}	11.88 ± 0.09^{b}
	60	67.5 ± 3.22^{d}	65.78 ± 1.11^{bc}	0.23 ± 0.02^{d}	12.13 ± 0.02^{b}
	70	61.5 ± 3.34^{c}	65.12 ± 1.63^{b}	−0.42 ± 0.01^{c}	12.16 ± 0.72^{b}
	80	61.0 ± 2.34^{c}	67.22 ± 0.45^{bc}	−1.0 ± 0.02^{b}	11.11 ± 0.24^{ab}
5	50	55.5 ± 2.98^{a}	59.73 ± 1.83^{a}	−1.33 ± 0.00^{a}	11.16 ± 0.82^{ab}
	60	56.5 ± 3.23^{ab}	65.25 ± 1.21^{b}	−0.24 ± 0.01^{c}	11.8 ± 0.03^{ab}
	70	63.00 ± 3.45^{cd}	65.44 ± 2.21^{b}	1.13 ± 0.02^{e}	10.68 ± 0.11^{a}
	80	79.50 ± 2.88^{f}	69.60 ± 0.27^{c}	3.53 ± 0.29^{f}	15.16 ± 0.26^{c}

Values are means ± standard deviation ($n = 3$); Different letters in the same column indicate significant differences ($P < 0.05$) using Tukey's HSD (honestly significant difference) test. UNT: untreated yam slices sample; *L**: lightness; *a**: redness; *b**: yellowness.

Table 7
Effect of ascorbic acid pre-treatment and drying temperature on texture and colour of dehydrated yam chips.

Ascorbic acid concentration (%)	Drying Temperature (°C)	Texture	Colour		
		Hardness (N)	*L**	*a**	*b**
1	50	64.00 ± 3.08^{b}	61.56 ± 3.00^{a}	0.29 ± 0.02^{a}	10.13 ± 0.59^{b}
	60	58.00 ± 2.89^{a}	65.28 ± 2.05^{ab}	0.62 ± 0.06^{abc}	10.27 ± 0.61^{b}
	70	67.50 ± 3.23^{b}	61.47 ± 2.02^{a}	1.17 ± 0.06^{c}	11.51 ± 1.18^{b}
	80	78.00 ± 3.01^{c}	70.05 ± 0.51^{b}	6.39 ± 0.07^{e}	16.86 ± 0.92^{d}
5	50	63.50 ± 3.45^{b}	62.50 ± 2.27^{a}	4.26 ± 0.48^{d}	12.59 ± 2.15^{c}
	60	64.00 ± 2.47^{b}	63.41 ± 2.14^{a}	1.09 ± 0.00^{bc}	14.43 ± 0.86^{c}
	70	58.00 ± 2.39^{a}	64.31 ± 1.53^{ab}	4.29 ± 0.52^{d}	14.96 ± 0.96^{cd}
	80	54.00 ± 3.67^{a}	62.28 ± 2.16^{a}	0.38 ± 0.03^{ab}	6.57 ± 0.24^{a}

Values are means ± standard deviation ($n = 3$); Different letters in the same column indicate significant differences ($P < 0.05$) using Tukey's HSD (honestly significant difference) test. UNT: untreated yam slices sample; *L**: lightness; *a**: redness; *b**: yellowness.

growth, thus reduced acceptability, and that this could be caused by the Maillard reaction, which is a result of the use of available reducing sugars. Yellowness (*b**) was best maintained at 16.21 ± 0.23 after 4 min of 80 °C blanching (Table 5). It was best conserved for samples that had already been treated with citric acid at 5 %, 80 °C (15.16 ± 0.26) in Table 5. The highest value for samples of ascorbic acid was 16.86 ± 0.92 for 1 % at 80 °C (Table 7). The oxidative browning of yam is linked to phenolic chemicals, and this is what is thought to have caused the alteration in the colour indices [3].

3.3. Effective moisture diffusivity

D_{eff} values ranged from 8.12456×10^{-9} m^2/s to 1.0143×10^{-8} m^2/s for blanching, 8.33756×10^{-9} m^2/s to 1.0143×10^{-8} m^2/s for citric acid, 8.64185×10^{-9} m^2/s to 1.0143×10^{-8} m^2/s for ascorbic acid and 7.42469×10^{-9} to 1.0143×10^{-8} m^2/s for untreated pre-treatments in Table 8. The results demonstrated that the drying temperature had an impact on the moisture diffusivity in the yam chips as pre-treated samples at 80 °C had the highest D_{eff} value of 1.0143×10^{-8} m^2/s whereas the lowest D_{eff} value of 5.17294×10^{-9} m^2/s was recorded by the 5 % citric acid at 50 °C. One of the most crucial factors to consider while trying to optimize the drying process is internal moisture diffusion coefficient, which measures a product's capacity to get dehydrated under specific drying circumstances [50]. The D_{eff} values found in this study was recorded within the typical range of 10^{-12} - 10^{-8} m^2/s^{-1} for drying food products [30,54]. Ojediran et al. [55] reported a comparable rise in D_{eff} from 6.382×10^{-9} - 1.641×10^{-7} m^2/s for yam slices of *Dioscorea rotundata*; Falade et al. [35] reported increases from 9.92×10^{-8} - 1.02×10^{-7} m^2/s for both *Dioscorea rotundata* and *Dioscorea alata*; and the effective diffusivity of elephant foot yam slices increased similarly from 6.69×10^{-8} - 3.41×10^{-7} m^2/s with higher drying temperatures, according to Srikanth et al. [56]. D_{eff} values generally rose with temperature (50–80 °C), which led to a quicker dehydration of the yam chips. A higher temperature causes heat transfer rates to increase, which accelerates the movement of moisture from the center of the chips to the surface for evaporation [57]. Variations in D_{eff} values are caused by the dried material's moisture content, drying temperature, pre-treatments applied, drying equipment, and dried product compositional changes [57]. The high D_{eff} values at 80 °C support the conclusions made by Adu-Poku et al. [58] after they studied scanning electron micrographs of potato tissues. They ascribed the alteration in the potassium diffusion matrix through and out of potatoes to the variations in drying temperature.

3.4. Determination of energy consumption of drying system

The outcomes for the energy metrics of the dried yam chips under various pre-treatments and drying temperatures are presented in Table 9. The oven dryer's energy usage was calculated in kilowatt-hours.

Table 8
Effective moisture diffusivity for different pre-treatment methods at various drying temperatures.

Pre-treatment		Temperature (°C)	D_{eff} (m^2/s)
Blanching	1 min	50	5.69023×10^{-9}
		60	6.20753×10^{-9}
		70	8.08398×10^{-9}
		80	1.0143×10^{-8}
	2 min	50	6.08581×10^{-9}
		60	6.82625×10^{-9}
		70	7.30297×10^{-9}
		80	1.0143×10^{-8}
	3 min	50	5.93366×10^{-9}
		60	6.63353×10^{-9}
		70	7.5464×10^{-9}
		80	1.0143×10^{-8}
	4 min	50	5.56852×10^{-9}
		60	6.6741×10^{-9}
		70	8.07384×10^{-9}
		80	1.0143×10^{-8}
	5 min	50	5.46709×10^{-9}
		60	6.33939×10^{-9}
		70	8.12456×10^{-9}
		80	1.0143×10^{-8}
UNT		50	6.02495×10^{-9}
		60	6.01481×10^{-9}
		70	7.42469×10^{-9}
		80	1.0143×10^{-8}
Citric	1 %	50	5.31494×10^{-9}
		60	7.20154×10^{-9}
		70	8.33756×10^{-9}
		80	1.0143×10^{-8}
	5 %	50	5.17294×10^{-9}
		60	7.4044×10^{-9}
		70	7.4044×10^{-9}
		80	1.0143×10^{-8}
Ascorbic	1 %	50	5.5178×10^{-9}
		60	7.25226×10^{-9}
		70	8.64185×10^{-9}
		80	1.0143×10^{-8}
	5 %	50	5.70038×10^{-9}
		60	6.69439×10^{-9}
		70	8.44913×10^{-9}
		80	1.0143×10^{-8}

3.4.1. Total energy consumption (E_t)

It can be inferred from Table 9 that the overall energy required for drying blanched yam chips to achieve a constant weight under varying temperatures (50, 60, 70, and 80 °C) and blanching times (1, 2, 3, 4, 5 min) and control ranged from 43.68 to 81.12 kWh with the drying duration ranging between 26 h and 15 h correspondingly. E_t for citric acid varied with drying temperature (50, 60, 70, and 80 °C) and concentration (1 and 5 %) from 46.80 kWh to 93.60 kWh with drying duration from 30 h to 16 h. Energy usage for ascorbic acid varied from 49.92 to 93.60 kWh with drying times ranging from 30 to 17 h under varied drying temperatures of 50, 60, 70, and 80 °C and concentrations of 1 and 5 %. It can be realized from the results that blanching at 1, 2, 3, and 4 min utilized the least amount of total energy at 80 °C when compared to the other pre-treatments at other drying temperatures. According to Ando et al. [59], blanching is a quick heat treatment that causes the moisture content to drop so that drying may start. Since there is less water evaporating during the drying process, it results in shorter drying times translating to lower energy usage. Again, the least energy consumption experienced by all samples at 80 °C corroborates findings by Song et al. [50], that an increase in drying temperature and a reduction in drying time result in significant energy savings in a drying system.

3.4.2. SMER

The lowest SMER value (0.0019kg/kWh) was obtained by blanching for 5 min at 50 °C, while the highest SMER value (0.0043 kg/kWh) was obtained by blanching for 2 and 4 min at 80 °C, respectively (Table 9). While the highest value of 0.0039 kg/kWh was observed at 5 % 80 °C for citric acid, the lowest value of citric acid, 0.0018 kg/kWh was reported at 1 % and 5 % of 50 °C. Similarly, the highest value of 0.0036 kg/kWh was likewise found at both 1 and 5 % at 80 °C respectively for ascorbic acid, whereas the lowest value of 0.0018 kg/kWh for ascorbic acid was reported at 1 and 5 % at 50 °C. As can be observed, drying time decreased as drying temperature rose because moisture removal from samples increased. The outcome is consistent with comparable findings from Refs. [60–62] who conducted studies on mango, red chili, and tomatoes respectively. To increase SMER value more moisture must be eliminated through the drying process.

Table 9
Energy consumption in the drying of yam chips.

Pre-treatment & Time (min)		Temperature (°C)	Total energy (E_t), (kWh)	SMER (kg/kWh)	MER (kg/h)	SEC(E_s) (kWh/kg)
Blanching	1 min	50	81.12	0.0020	0.006	494.63
		60	74.88	0.0023	0.007	430.34
		70	62.40	0.0029	0.009	344.75
		80	43.68	0.0041	0.013	241.32
	2 min	50	81.12	0.0021	0.007	458.30
		60	71.76	0.0024	0.008	400.89
		70	62.40	0.0028	0.009	346.66
		80	43.68	0.0043	0.013	232.34
	3 min	50	81.12	0.0020	0.007	480.00
		60	71.76	0.0025	0.008	390.00
		70	65.52	0.0027	0.009	364.00
		80	43.68	0.0042	0.013	234.83
	4min	50	81.12	0.0020	0.006	494.63
		60	74.88	0.0023	0.007	423.05
		70	62.40	0.0028	0.009	348.60
		80	43.68	0.0043	0.013	232.34
	5min	50	81.12	0.0019	0.006	507.00
		60	71.76	0.0026	0.008	379.68
		70	62.40	0.0028	0.009	348.60
		80	46.80	0.0038	0.012	260.00
UNT		50	81.12	0.0020	0.006	482.85
		60	74.88	0.0024	0.008	402.58
		70	65.52	0.0026	0.008	374.40
		80	46.80	0.0038	0.012	261.45
Citric acid	1 %	50	93.60	0.0018	0.006	534.85
		60	71.76	0.0024	0.008	400.89
		70	62.40	0.0029	0.009	344.75
		80	49.92	0.0037	0.012	268.38
	5 %	50	93.60	0.0018	0.006	528.81
		60	71.76	0.0025	0.008	398.66
		70	62.40	0.0029	0.009	344.75
		80	46.80	0.0039	0.012	250.26
Ascorbic acid	1 %	50	93.60	0.0018	0.006	534.85
		60	71.76	0.0024	0.008	400.89
		70	62.40	0.0029	0.009	344.75
		80	49.92	0.0036	0.012	274.28
	5 %	50	93.60	0.0018	0.006	534.85
		60	74.88	0.0023	0.007	418.32
		70	62.40	0.0029	0.009	344.75
		80	49.92	0.0036	0.011	274.28

SMER: specific moisture extraction rate; MER: the moisture extraction rate; SEC: the specific energy consumption (SEC).

3.4.3. MER

As indicated in Table 9**,** MER values were found to increase with increasing drying temperature. The corresponding range of values for all the processes of blanching pre-treatments, citric and ascorbic acid pre-treatments were 0.006–0.013 kg/h, 0.006–0.012 kg/h, and 0.006–0.011 kg/h. The findings suggest that the MER of yam chips was more significantly influenced by the rising dryer temperatures than by the various pre-treatment techniques and circumstances. According to Stawreberg & Nilsson [63], raising the dryer's temperature resulted in a greater internal airflow rate, which raised the sample's MER.

3.4.4. SEC (E_s)

The maximum SEC value for all blanching samples was 507.0 kWh/kg at 5 min at 50 °C, while the lowest value was 232.34 kWh/kg at 2 and 4 min at 80 °C (Table 9). The highest and lowest SEC values for citric acid samples, 534.85 kWh/kg and 250.26 kWh/kg, were recorded at 1 % and 5 % at 50 °C and 5 % at 80 °C, respectively. The highest and lowest values for ascorbic acid samples, 534.85 kWh/kg and 274.28 kWh/kg, were also noted at 1 % and 5 % at 50 °C and at 1 % and 5 % at 80 °C. As a consequence of the findings, it can be concluded that raising the temperature reduced the amount of energy needed to dry yam chips. Terebinth was shown to require less specific energy than convective drying due to the higher temperatures of the air employed in infrared drying. The SEC during drying was similarly reduced by terebinth pre-treatments with ultrasound and blanching [64].

3.5. Thermodynamics parameters

3.5.1. Activation energy (E_a, enthalpy change, Gibbs free energy, and entropy change)

Thermodynamic parameters were assessed in order to have a thorough grasp of the physical, chemical, and biological characteristics of dried yam chips (Table 10). The energy needed to get a reaction into its active state is commonly referred to as the E_a. The

Table 10
Determination of activation energy (E_a), enthalpy (ΔH), Gibbs free energy (ΔG), and entropy change (ΔS) for dried yam chips at varied temperatures.

Pre-treatment & Time (min)		Temp. (^oC)	k (1/Min) $\times 10^{-3}$	R^2	E_a (kJ/mol)	R^2	ΔH(kJ/mol)	ΔG(kJ/mol)	ΔS(kJ/mol)
Blanching	1min	50	0.00056	0.985	18.87	0.957	16.18	188.44	−533.0
		60	0.00061	0.916			16.10	194.11	−534.3
		70	0.00080	0.908			16.02	199.27	−534.0
		80	0.00100	0.921			15.93	204.49	−533.9
	2 min	50	0.00060	0.954	15.05	0.873	12.37	188.26	−544.3
		60	0.00067	0.922			12.28	193.85	−545.0
		70	0.00072	0.854			12.20	199.56	−546.0
		80	0.00100	0.855			12.12	204.49	−544.7
	3 min	50	0.00059	0.986	16.37	0.928	13.69	188.32	−540.4
		60	0.00065	0.911			13.60	193.93	−541.3
		70	0.00074	0.883			13.52	199.47	−541.9
		80	0.00100	0.954			13.44	204.49	−541.0
	4 min	50	0.00055	0.972	19.90	0.985	17.21	188.49	−530.1
		60	0.00066	0.988			17.12	193.91	−530.7
		70	0.00080	0.904			17.04	199.27	−531.1
		80	0.00100	0.913			16.96	204.49	−531.0
	5 min	50	0.00054	0.988	18.84	0.994	16.15	188.54	−533.5
		60	0.00063	0.940			16.07	194.05	−534.2
		70	0.00080	0.901			15.99	199.25	−534.1
		80	0.00100	0.943			15.90	204.49	−534.0
UNT		50	0.00059	0.984	19.30	0.815	16.61	188.28	−531.2
		60	0.00059	0.935			16.53	194.20	−533.3
		70	0.00073	0.863			16.44	199.51	−533.5
		80	0.0010	0.923			16.36	204.21	−531.9
Citric acid	1 %	50	0.00052	0.990	18.40	0.900	15.71	188.62	−535.1
		60	0.00071	0.881			15.63	193.70	−534.5
		70	0.00082	0.882			15.55	199.18	−535.1
		80	0.00100	0.881			15.46	204.49	−535.3
	5 %	50	0.00051	0.977	20.62	0.977	17.94	188.69	−528.4
		60	0.00073	0.865			17.85	193.62	−527.6
		70	0.00073	0.923			17.77	199.52	−529.7
		80	0.00100	0.875			17.69	204.49	−529.0
Ascorbic acid	1 %	50	0.00054	0.994	19.05	0.989	16.36	188.52	−532.8
		60	0.00072	0.934			16.28	193.68	−532.5
		70	0.00085	0.931			16.19	199.08	−533.0
		80	0.00100	0.839			16.11	204.49	−533.4
	5 %	50	0.00056	0.981	18.59	0.993	15.90	188.43	−533.9
		60	0.00066	0.954			15.82	193.90	−534.5
		70	0.00083	0.947			15.74	199.14	−534.5
		80	0.00100	0.872			15.65	204.49	−534.7

Temp.: temperature (°C); R^2: regression coefficient.

values of the E_a calculated from plot of kelvin 1/temp (k^{-1}) against reaction rate constant k (min^{-1}) are shown in Fig. 4 (A, B and C). It is evident from the Arrhenius plots that the slope of the plots corresponded to the *(E_a)* for the dried yam chips. This was supported by the natural logarithm of the rate constant versus1/K. Accordingly, the dried yam chips' E_a ranged from 15.05 to 20.62 kJ/mol (R^2 = 0.815–0.994) based on the different drying conditions. Throughout the drying process, lower E_a values are correlated with higher moisture diffusivity [65]. The reported enthalpy change values for the pre-treatments of blanching, citric acid, and ascorbic acid were 12.12–17.21 kJ/mol, 15.46–17.94 kJ/mol, and 15.65–16.36 kJ/mol, respectively. The equation (ΔH = E_a-RT) states that ΔH is affected by temperature variation. Temperature changes can be connected to variations in ΔH levels, and it has been observed that ΔH and drying temperature are directly correlated. Lastly, the drying process appears to have been an endothermic reaction as indicated by positive ΔH values [66]. Therefore, the computed ΔH values for the pre-treatments of blanching, citric acid, and ascorbic acid were 12.12–17.21 kJ/mol, 15.46–17.94 kJ/mol, and 15.65–16.36 kJ/mol, respectively. Using Gibbs free energy (ΔG), dried yam chips' spontaneity of reaction was calculated. Dried yam chips' (ΔG) values ranged from 188.28 to 204.49, 188.62–204.49, and 188.43–204.49 kJ/mol, showing that the pre-treatments' reaction was not spontaneous indicative of lower stability in the drying system [66]. The nearness of the values is an indication that the total energy rise in the drying system at the method of the chemical agents and the molecular compounds formation were comparable for several temperatures. For example, gelatinizing starch at 50 °C and 60 °C, it is expected chips will gelatinize more quickly at 60 °C than at 50 °C. The yam chips produced by this expedited procedure may have a more consistent and even texture than those dried at 50 °C. Once more, yam chips at 60 °C might need less energy to break the gelatinization barrier than those at 50 °C. By measuring the variation in entropy (ΔS) for slices of yam chips, the disorder variation of molecules in a system was assessed. The dried yam chips' values for entropy change (ΔS) varied from −533 to (−546), −527.6 to (−535.3), and −532.5 to (−534.7) kJ/mol. The negative increase in the entropy change indicates a decrease in the randomness or disorder of the system [66,67]. This reduction suggests a more ordered state during heat treatment which is generally unfavourable according to the second law of thermodynamics.

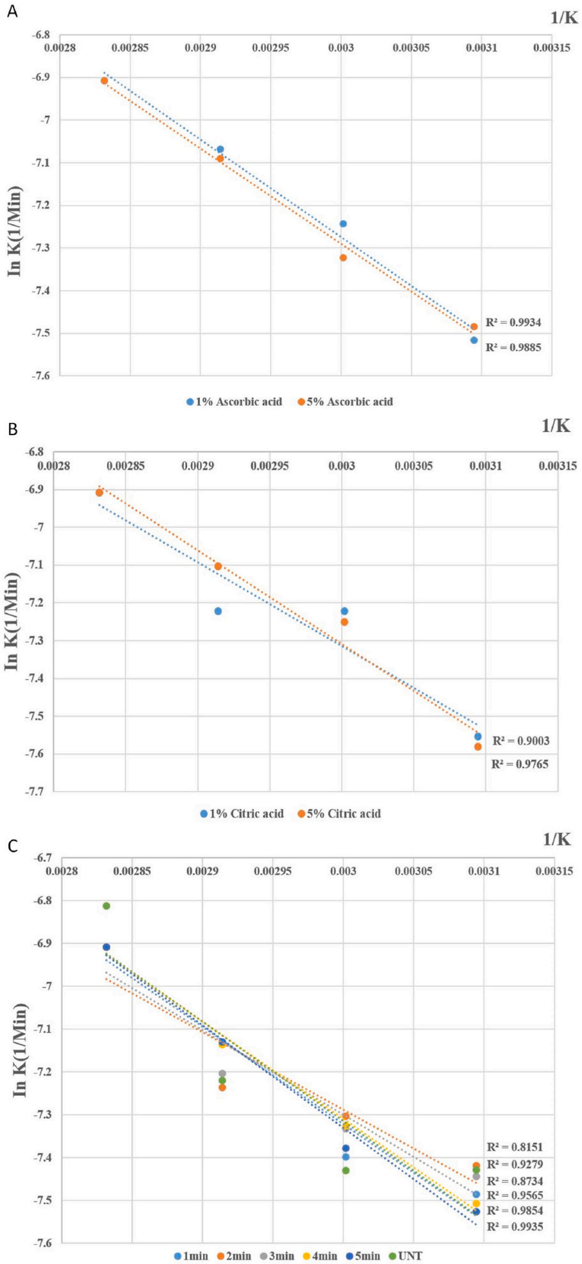


Fig. 4. Influence of temperature and reaction rate constant on E_a for pre-treatment samples (A: ascorbic acid, B: citric acid, and C: untreated and blanched samples).

4. Conclusions

The influence of pre-treatment on the drying dynamics of yam chips revealed that drying was faster at higher temperatures of 80 °C due to the speedy removal of moisture than at lower temperatures of 50 °C, 60 °C, and 70 °C. The asymptotic model was found to be the suitable descriptive model for predicting water profile in the pre-treated yam chips compared to the Lewis and Page models because it corroborated with all tested fitting curve parameters. Instrumental textural analyses revealed that 4 min blanched yam chips were of suitable quality attribute. Whereas, pre-treated yam chip's colour indices inferred a significant effect of pre-treatment and drying temperature on the final products L^*, a^*, and b^* values. The values of D_{eff} (5.17294×10^{-9} m^2/s) obtained for 5 % citric acid pre-treated samples at 50 °C was the least while that of 1.0143×10^{-8} m^2/s was the highest value for all pre-treated samples at 80 °C indicating moisture diffusivity in the yam chips is affected by the drying temperature. The activation energy (E_a) value ranged from 15.05 to 20.62 kJ/mol exhibiting the effect of temperature on the diffusivity. Energy consumption in the drying system decreased with increasing temperature with blanched samples attaining the least energy usage of 43.68 kWh. Concisely, 4 min blanching, 5 % citric, and 1 % ascorbic acids at 80 °C were found to be the optimum pre-treatments conditions. Also, the functional mechanism of the pre-treatments conditions resulted in the lower moisture contents of samples after drying, suitable textural hardness attribute, appreciable lightness in colour of dried yam chips and lower energy consumption rates during drying.

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Data availability

No data associated with the study has been deposited into a publicly available repository. Data is included in article/supp. material/referenced in article.

CRediT authorship contribution statement

Evans Ntim Amedor: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Frederick Sarpong:** Writing – original draft, Supervision, Resources, Methodology, Investigation. **Paa Kwasi Bordoh:** Writing – review & editing, Validation, Supervision. **Evans Frimpong Boateng:** Writing – review & editing, Visualization, Validation. **James Owusu-Kwarteng:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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